BBC RD 1973/29

1969
THE QUEEN'S AWARD TO INDUSTRY

RESEARCH DEPARTMENT

REPORT

DIGITAL TELEVISION RECORDING: a review of current developments

A.H. Jones, B.Sc.(Hons.)

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION November 1973

BBC RD 1973/29
UDC 681.327.13:621.397

DIGITAL TELEVISION RECORDING: A REVIEW OF CURRENT DEVELOPMENTS

A.H. Jones, B.Sc. (Hons.)

Summary

This report examines current developments in high density digital recording in the light of the present and probable future requirements of broadcast television recording. Consideration is given to the techniques most likely to feature in future digital television recorders and it is concluded that operational machines could be made using magnetic heads and tape but that the long-term solution may well be provided by one of the newer technologies using laser beams.

Issued under the authority of

P. Rainger

Head of Research Department

Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION
November 1973
(PH-112)

DIGITAL TELEVISION RECORDING: A REVIEW OF CURRENT DEVELOPMENTS

(PH-112)

DIGITAL TELEVISION RECORDING: A REVIEW OF CURRENT DEVELOPMENTS

A.H. Jones, B.Sc.(Hons.)

1. Introduction

The potential benefits of digital recording bave been discussed from the time that the application of digital techniques to broadcast television was contemplated. It was readily appreciated that the particular advantage of digital processing, the preservation of the original signal quality with mathematical precision, would be especially valuable in the recording area and would give greater freedom to programme makers in using editing techniques involving extensive copying. A previous report[1] reviewed a number of possible methods for recording digital signals and concluded that a technique suitable for television would ultimately emerge, and recommended that magnetic tape recording using conventional heads could meantime provide a useful basis for experiment.

Since that report was written, a considerable amount of work has been carried out on digital signal processing, and some basic investigations have been made into digital magnetic recording. As a result of this work it is now possible to assess more accurately the potential advantages of digital recording and developments have moved appreciably closer to the point at which the basic specification of a digital magnetic recorder could be defined. Meantime, fundamental work on new recording technologies has been done in a number of laboratories including BBC Research Department.

This report gives a broad up-to-date account of these developments and attempts to predict those approaches to high-density recording, now being pursued, which are likely to prove most suitable. First, however, a brief outline will be given of the present and likely future technical requirements of the television recording area.

2. Present-day and desirable future recording facilities

Video tape recording plays a major role in television programme making, and the recording machines at Television Centre are heavily employed. At any one time a machine may be used for recording the whole or sections of a programme, replaying to the network, or for rehearsals, editing, dubbing, or providing programme inserts.

A considerable amount of time is spent on editing, each one-hour programme requiring an average of eight hours of editing time. The machines can readily be coupled together in pairs, and editing is carried out mainly by running a pair in synchronism and then copying from the one to the other. Video tape editing suffers from the disadvantage, as compared with film, that the tape cannot easily be inched forward or backward to find the right frame at which to edit, but it has the valuable advantage that it is possible to arrange to rehearse the cut before making a final decision. A useful semi-automated aid to the process using a time-code address system has been installed. Bearing in mind that the cost of an editing channel is much less than that of a studio, it is likely that, as editing aids become more sophisticated, the demand for editing facilities will grow. A technique sometimes used involves the provision of a lower-grade copy of the original tape, made using a cheap helical scan machine, which enables the programme maker to arrive at editing decisions without tying up expensive quadruplex machines and their operators. This technique could ultimately lead to a largely automated process, the decisions being fed into a computer which would then control the editing operations carried out on the quadruplex machines. This presupposes, however that the remotely-operated high-grade machines used in the final programme assembly could be left largely unattended, so their reliability would need to be very high.

The present quadruplex machines are reasonably reliable, complete breakdowns being very rare, but minor problems of various sorts crop up from time to time. Most failures are due to mechanical difficulties involving brakes, electrical contacts, pneumatic components, and so on. However, this situation needs to be viewed against the background of extensive routine maintenance necessary to keep the machines in good order; this occupies something like half a day a week, with further adjustments to optimise recording parameters taking about an hour every two or three days. A set of heads lasts for about 250 hours; if the heads are not regularly serviced, colour banding appears and compatability between machines suffers.

The transmission recording is generally a second-generation tape, i.e. a first copy of the original, but if may often contain third-generation inserts. Fourth- and fifth-generation material is not uncommon, however, although multiple generations are avoided wherever possible. Some tape is re-used after checking, but much of it finds its way into the archives. The tape library now represents a large capital investment, and tape costs account for a sizeable proportion of the total recording cost.

With a well adjusted machine, a typical first-generation (i.e. an original) tape gives a fully acceptable signal with a K-rating of 1½%, 4° differential-phase distortion and 4% differential-gain distortion. The signal-to-noise ratio is at least 43 dB but moiré patterning, head banding and l.f. disturbances make the picture look somewhat worse than this suggests. The pictures from a first-generation tape would be graded about 2 on the EBU 6-point impairment scale, and in the case of the more usual second-generation tape the grading would be 2½. If further generations are involved, and they often are, the impairments begin to get more noticeable, depending on picture content. The quality of the audio signal also shows a marked deterioration with further generations of copying.

These picture impairments are mainly due to non-linearities in the overall transfer-characteristic, limitations

in the frequency response of the head/tape system, the basic granularity of the medium, timing irregularities in the transport mechanism, and mismatch in the alignment and performance of the heads. Ingeneous mechanical and electro-mechanical systems have been devised to minimise these problems, and sophisticated analogue circuitry has been developed to provide correction. Recently, the basic problems themselves have been somewhat eased by improvements in heads and tape.

A variety of different machines based on helical scanning are currently being developed, but the optimum helical format has not yet been established. Meantime quadruplex recorders could be made to take advantage of improvements in heads and tape, either as a reduction of tape consumption or as improvements in signal-to-noise ratio (by modifying the f.m. parameters to exploit the wider bandwidth available).

Further improvements in analogue recording can be provided by converting the replayed signals to digital form for subsequent processing. The availability and relative cheapness of digital storage, for example, makes it an attractive technique for timing correction. It would clearly be better, however, for the signal to be in digital form throughout the transducer/medium/transducer stages of the recording/replay process where most of the troubles associated with analogue recording originate. In principle, it would then be possible to obtain, in the recording area, the advantages provided by full digital working, i.e. the preservation of the original signal quality with a mathematical precision regardless of the number of copying processes, immunity from circuit drifts, and the almost complete absence of complicated mechanical and electronic alignment and adjustment. These ideal characteristics would not in practice be fully met; some undetected digital errors might arise, for example, and there might need to be some residual routine adjustment. If a digital recorder is to be viable, however, such departures from the ideal must be minimal.

Thus the chief benefits to be expected from digital recording are an extremely high signal quality, 'hands-off' operation, automatic monitoring and minimum maintenance. These features could give rise to significant cost savings but such savings might be absorbed if digital recording demanded an increase in the cost of the medium; in fact it is desirable that both the cost, and the physical size and weight, of the medium be reduced. With signal quality no longer very dependent on the number of copying processes, digital recording will doubtless make editing even more attractive than it is at present, and the particular suitability of digital techniques to automated editing should therefore be exploited to the full.

A reduction in the capital cost of the equipment is, of course, always desirable. For most studio applications the size of the present machines is not an undue embarrassment, but there is a need for a lightweight portable recorder, perhaps with replay facilities limited to an arrangement for confirming that the recording is satisfactory.

All of the above aspects will need to be borne in mind when a decision as to the suitability of a proposed digital recorder is made.

3. Digital signal parameters

The television signal chain may conveniently be divided into a number of inter-connected areas, e.g. signal origination in cameras and telecines, mixing for programme assembly, recording, standards conversion, distribution, etc. The application of digital processing to each of these areas is currently being investigated to determine the form in which the digital signal should be handled in each area and the form in which it might best be passed from one area to another. Whilst no definite conclusions have yet been reached, it can be argued, particularly if systems based upon digital methods were to be inserted into the signal chain in a somewhat piecemeal fashion, that the signal at the interfaces between areas should be in digital PAL form employing 8-bit words with a sampling rate equal to thrice sub-carrier frequency, the samples being symmetrically disposed about the unswitched axis. Thus the serial data rate at the interfaces would be approximately $3 \times 4{\cdot}43 \times 8 = 106$ Mbits/sec., plus any extra allowed for parity protection. Other proposed forms of coding, e.g. digital Y, U and V, require a similar bit rate. It would appear, therefore, that digital television recorders ought to be capable of dealing with a data rate of this order.

The precision of digital processing, however, is such that it is possible to employ a number of techniques which lower the required bit-rate by removing redundancy and exploiting the limited perception of the observer; such techniques would have been impracticable using analogue processing. Experimental systems of bit-rate reduction are being investigated and present indications are that it may be possible to halve the above rate without causing perceptible picture impairment.

Bit-rate reduction applied to a digital recorder should enable a valuable saving in medium consumption to be achieved and might reduce the amount of electronic processing required in the machine.

The influence of bit-rate reduction methods on possibilities for minimising the effects of digital errors is not yet fully explored, moreover it is not yet known how many times the proposed techniques can be applied during the 'history' of a signal before a given degree of overall picture impairment is reached. Indeed, it is expected that an experimental digital television recorder now being constructed will prove to be a useful tool in these investigations.

It appears likely, however, that digital television recorders will ultimately be required to handle no more than 60 Mbits/sec., though it is intended that the experimental machine should handle the full bit-rate referred to above.

It is anticipated that imperfections will occur in whatever recording medium is finally adopted, and that these will give rise to digital errors, probably in the form of lengthy bursts. Work carried out so far on error conceal-

ment suggests that a modest increase in bit-rate will provide for an effective means of parity protection and that it will be possible to process the replayed signal even in the presence of bit-rate reduction so as to prevent the observer from detecting these unexpected and hopefully infrequent events.

4. Possible recording techniques

Digital television recording may be considered to be a particular form of high-speed, high-density data recording. The demand for the efficient storage of large quantities of digital data is increasing, and several of the techniques developed to satisfy this need potentially have application to television.

Bulk data storage is still mainly provided by conventional magnetic tape recording. Substantial improvements have been made in both heads and tape during the last few years, and digital packing densities are still increasing. It is generally accepted, however, that the most recent developments approach the limit attainable with this technique, and that the long-term future of bulk data storage lies in the development of new recording technologies, probably making use of laser or electron beams. Several of these new approaches to digital recording were described in the previous report.[1]

It is worth bearing in mind, however, that such developments are mainly directed to the setting up of large data banks associated with computers and one of the important conditions governing their design is that it must be possible to extract relatively small quantities of data very rapidly from the very large total stock. This requirement contrasts very much with that of digital television in which it is necessary to record and replay, at high speed, a very large quantity of data as a continuous sequence. When rapid access is required to only part of the total recorded information, it is realistic to consider using a stack of rigid substrates on which recording medium has been deposited as 'pages', with an arrangement somewhat similar to a mechanical 'juke box' that enables very rapid access to the page of information required. Whilst in principle the same technique could be employed for television, it would clearly be more satisfactory to use a flexible medium capable of being wound on a reel.* This arrangement is then similar to that of present-day VTRs, wherein two-dimensional scanning of a moving medium is achieved by deflecting the transducer in one direction whilst moving the medium in another.

New technologies are also being developed in connection with analogue recording systems for home video players. Reference will be made to these developments in so far as they are relevant to possible systems of digital recording.

* Given a sufficient packing density, e.g. one second of television (say 60 — 100 Mbits) per square centimetre, rigid recording media may be acceptable for short excerpts of programme, e.g. for requirements at present fulfilled by the H.S.100 disc machine.

4.1. Electron and laser beam recording

Both electron beams and laser beams can be focused to very fine spots and hold out the possibility of an improvement of about 50 : 1 in digital packing density as compared with that achieved using conventional magnetic tape and heads.

A comparison of the properties of electron and laser beams was given in the previous report.[1] Electron beams are easily generated, modulated and deflected, but they have the disadvantage that they require a vacuum of about 10^{-6} torr in which to operate, and the medium must therefore be suitable for use in the vacuum. Laser beams are also easy to generate and can be made to have very high power. They do not require a vacuum but they are more difficult to modulate and deflect. Electro optic devices can be used for modulation, as previously described,[1] and also for deflection.[2]

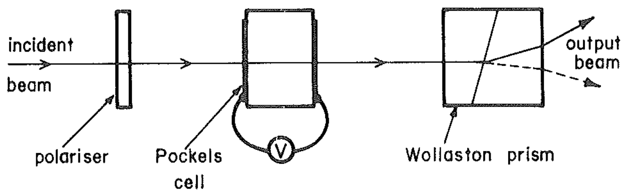

Fig. 1 - Electro-optic ('digital') light deflector

Fig. 1 shows one method by which an electro optic Pockels cell may be used for deflection. The cell rotates the plane of polarisation of the incident light beam, and the emergent light is then passed to a birefringent prism which deflects light in two directions; with the correct orientation of the prism, the amount of light deflected in one direction, compared to that deflected in the other, depends on the direction of polarisation. n of these so-called 'digital deflectors' can be arranged to provide a total of 2^n different beam-deflection angles, and they can of course be arranged to cover a two-dimensional field if required. An interval of about one microsecond is required to switch from one deflection angle to another.[3]

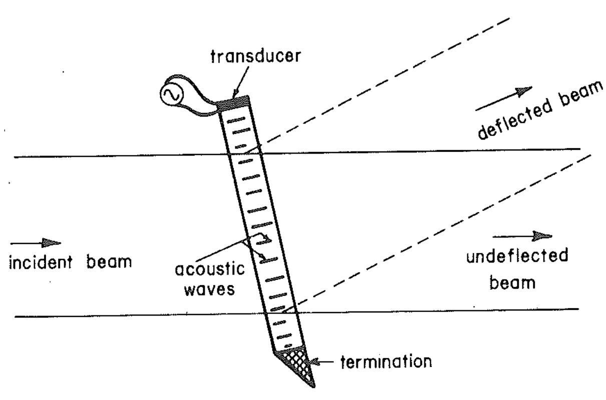

Fig. 2 - Acousto optic light deflector

An alternative deflector, described more fully in a separate report,[4] is shown in Fig. 2. An ultrasonic wave

propagated through a Bragg cell produces a spatial variation in the refractive index of the cell material, and the cell then operates as a diffraction grating of variable pitch; the angle through which the light is deflected depends on the frequency of the ultrasonic wave. To achieve good resolution with such a device, the beam should be several millimeters in width as it passes through the cell, so as to encompass many cycles of the grating, but this limits the speed with which the ultrasonic wave corresponding to one deflection angle can be replaced by another (as a result of the finite time required for the acoustic wave to traverse the active portion of the cell). In practice, a resolution corresponding to 500 separately identifiable spots across the field of deflection can be obtained, with a linear scan, in about a television line period.

Thus the speed at which both of the above devices can operate is limited. Neither are suitable for the bit-by-bit recording of digital television signals unless several laser beams can be deflected in parallel. To switch a laser beam to, say, 10^8 separate positions every second would require the use of a mechanical deflector, e.g. a rotating polygon, possibly augmented by an array of fibre optic pipes to transform a circular scan pattern into a linear one.

When employing lasers for digital recording, however, it is possible to make use of their coherence properties by recording holograms corresponding to groups of bits rather than dealing with each bit separately. A comprehensive explanation of the principles of holography, and an account of an investigation into its potential use for recording is given in two other reports.[5,6] A third[7] describes recent work carried out on the recording of micro-holograms on photographic film. The following account is therefore provided merely as a brief summary of the technique.

Holography is a method of recording the optical wavefront, obtained from an object illuminated by coherent light, by mixing the light reflected from or transmitted by the object with a reference beam to form a standing wave pattern. When the recorded pattern is subsequently illuminated by the reference beam alone, an image of the original object is reconstructed by diffraction.

This technique is particularly attractive for recording digital bit-patterns; it potentially overcomes two of the problems to which high-density, bit-by-bit recording is particularly susceptible. First, for the order of packing density required for television recording, a system in which individual bits are recorded in separate positions on the medium is very susceptible to defects, e.g. dirt, scratches and so on. Secondly, in such a system it is necessary to track the recorded information accurately in order to recover the signal, and this imposes severe mechanical constraints. Holography provides a convenient technique for spreading the information describing each bit over a relatively large area of the recording medium and thus reduces the susceptibility both the defects in the medium and to tracking errors; it is possible, for example, to shift the position of the hologram with regard to the reference beam without altering the position at which the image is reconstructed. This property is exploited in the R.C.A. Holotape domestic player;[8] as the tape containing the holograms is moved, the reconstructed images are 'lap dissolved', one frame to the next. A further advantage of holography is that the optical systems required for recording and replaying the signal are relatively simple.

About the same amount of laser power and about the same area of medium are required to record the hologram of a given number of bits as to record the bits individually. However, holographic recording involves deflecting the beam to a smaller number of positions, so the frequencies with which the beam has to be moved to a new position and the laser has to be switched are both reduced. This can be a very useful advantage.

Clearly, therefore, it would be very advantageous to involve as many bits as possible in each hologram; however, the number is limited in practice by the availability of suitable modulator and sensor arrays.

A modulator array is needed in order to compose the 'page of information' (group of bits) from which the hologram is made. Two types of modulator have been proposed for real-time holographic recording. One type uses nematic liquid crystals sandwiched between two conductive layers;[9] one of these layers is continuous, the other being broken up into a mosaic of elements connected to an electronic register in which the binary data is temporarily stored. With no voltage between the layers, the liquid crystal is transparent; when a voltage is connected the light is scattered. These devices provide a high contrast ratio and require very little power, but their switching times are at present of the order of several milliseconds and this limits their usefulness in the application under consideration.

A more promising technique for page composing makes use of ferroelectric ceramics based on lead zirconate titanate or PLZT. These are electro-optic Pockels cell devices and can readily be fitted with an array of suitable electrodes. A notable development along these lines consists of a PLZT crystal with a number of conducting fingers on 300 micron centres.[10] When voltages of no more than about 200 volts are connected appropriately to these, the beam can be switched on or off in 100 nanoseconds with an optical-transmission on/off ratio of greater than 100 to 1.

The development of solid-state sensor arrays for reading the bit-patterns reconstructed from holograms is proceeding in several laboratories.[11] Linear arrays of up to 1024 elements and two-dimensional arrays of about 250 elements square can now be obtained; they consist either of photodiodes addressed in sequence by associated shift registers, or of photo-sensitive bucket-brigade or charge-coupled devices. Their maximum clocking rates (and hence bit rates) are at present limited to only a few MHz, so it would be necessary to use a number in parallel, perhaps with fibre-optic pipes to convey the light to them from the reconstructed image.

The present state of development of modulator and sensor arrays is such that it is more realistic, at this stage, to consider holograms containing a relatively modest number of bits. If, in recording the holograms, bit-cells were arranged in a line at right angles to the direction of motion

of the recording medium, the recorded wave patterns would lie in the direction of motion, and this would avoid the need for a short exposure to prevent blurring.

Electron-beam holograms are in theory possible, but the coherence necessary within the beam has in practice only been achieved by restricting the size of the source to the point where unacceptably long exposure times are necessary.

Electron and laser beams can be made to interact with many substances, and a large number of processes have been investigated to see if they could be used in recording. The potential media range from the well known photographic films through alkali-halide crystals, magneto-optical materials, photo-activated liquid crystals, photochromic materials, electro optic materials, photo-conductive-thermoplastic 'sandwiches', dichromated gelative, photo-resists, photopolymers and thin metal films.

Several of these media are not likely to prove practicable for television; the remainder can be divided into two classes. Those in the first use a relatively low-power electron or laser beam to create what amounts to a 'latent image' which is subsequently developed into a readable image by taking energy from a different source. The second class of materials use a high-power laser beam to form the image directly by heating the medium.

As an alternative classification, the potential media may be divided into those which are re-usable and those which are not.

There are two broad fields of application for video recording, namely programme assembly and archival storage; the first requires a re-usable medium, preferably with instant replay, the second demands neither. It follows that, in principle, two different recording technologies could be used, one for assembling the programme and the other when long-term storage is required. Both systems should operate in real time.

The following survey of proposed electron and laser beam systems categorises them according to which type of beam is used, whether holography is employed, and which medium is adopted.

4.1.1. Electron beam: photographic film

An electron beam recorder of the type suggested in the previous report[1] has been developed by the Ampex Corporation;[12] it is a basically analogue device, but could be adapted for digital operation. A bandwidth of 100 MHz and a SNR of 23 dB (peak-peak signal/rms noise) have been achieved and 10 minutes of recording can be accomodated on a reel of film, the film transport pump-down time to usable vacuum being 25 sec. Replay is somewhat different to that suggested in Ref. 1. After development the film is re-inserted into the recorder and the scanning electron beam focused onto its scintillator-coated surface. This produces a spot of light which scans the recorded image, and a photomultiplier mounted on the far side of the film collects the transmitted light. The reading beam is kept on track by the use of spot wobble which imparts a component to the output signal whose form changes if the mean position of the beam moves away from the centre of the desired track.

The scanning spot is 10 μm in diameter and the track pitch is 24 μm. This suggests a possible digital packing density of 2·6 Mbits per square inch. In other laboratory experiments[13] a density of 120 Mbits per square inch has been achieved, but this would probably be unrealistic in a practical environment.

4.1.2. Laser beam: holographic: photographic film

Holographic memories are receiving attention in many laboratories and some systems of modest capability have already been sold. Work carried out at the Plessey Research Laboratories is probably as advanced as any in this field. Engineers there have predicted[14] that, using a linear array of bits for each hologram, it would be possible to construct a recorder working at 100 Mbits/sec., packing perhaps a day's output of television onto a single reel of film.

4.1.3. Electron beam: thermoplastic film

Very little has been reported in the literature about electron beam recording on thermoplastic tape since the previous report was issued. It appears that most of the known investigations into the thermoplastic medium have, since that time, been concentrated on its use with laser beams.

4.1.4. Laser beam: holographic: thermoplastic film

The thermoplastic medium is capable of extremely high definition and when combined with a photoconductor can be made to have a sensitivity equal to that of high-resolution photographic emulsions;[15] phase holograms can be produced which have a high readout efficiency.

The photoconductor is applied either mixed with the thermoplastic or forming a separate layer between it and a conductive backing sheet. The latter form of construction is indicated in Fig. 3(*a*). Four steps are involved in recording as shown in Fig. 3(*b*); they may in practice be combined into a fewer number. The complete 'sandwich' is first charged by a corona device to a voltage which is divided between the thermoplastic and photoconductive layers in inverse proportion to their capacitances per unit aera. The sandwich is then exposed to the light pattern that constitutes the hologram. Where the photoconductor is illuminated it discharges itself so that the original charge now appears across the thermoplastic layer alone. The electrostatic forces through the thermoplastic film are, however, left unchanged by the movement of charge through the photoconductor and a further charge is therefore added to the complete sandwich by a second exposure to the corona. This increases the field through the thermoplastic layer below the areas that were illuminated and a relief image constituting a phase hologram therefore appears when the medium is softened by applied heat.

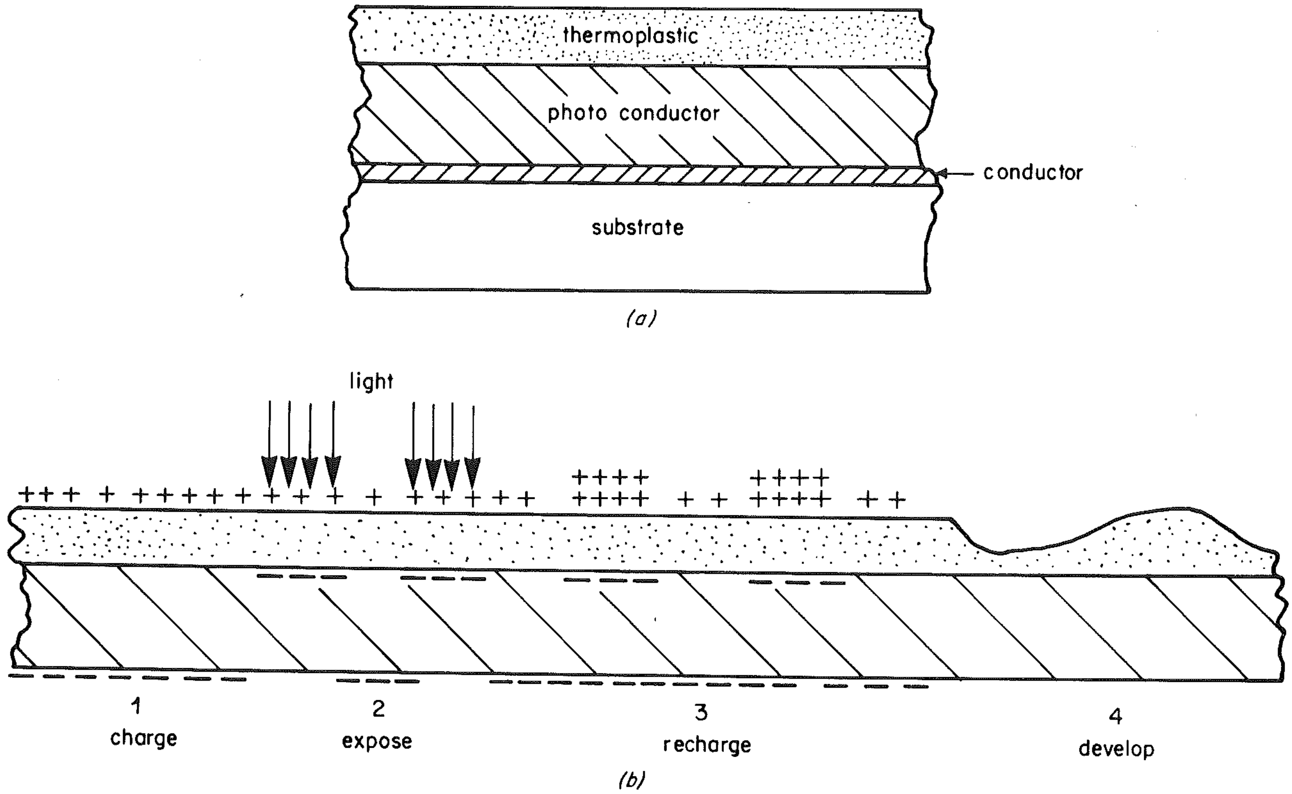

Fig. 3 - Laser beam thermoplastic recording
(*a*) Structure of medium (*b*) Method of recording

If the thermoplastic and photoconductive materials are combined as a single layer, the sensitivity of the medium is somewhat reduced, but the requirement for a second exposure to the corona device is removed.

As part of an investigation into the application of thermoplastic media to holographic recording, RCA have produced an experimental system which can easily be switched from the record to the replay mode by switching the plane of polarisation of the light emerging from the laser.[16] A schematic of the arrangement is shown in Fig. 4. After deflection the laser beam is split, by a device called a 'hololens', into an object beam which travels, via a page composer, to the storage medium and a reference beam which effectively passes directly to the medium. When the polarisation of the incident light is suitably switched, the object beam is arrested and the stored information is read out using the reference beam alone. This experimental recorder was constructed merely to explore the general feasibility of the method, and no attempt was made to achieve high speed or high packing density. However, a limiting resolution in excess of 4000 cycles per mm has been claimed for the thermoplastic medium[15] and packing densities comparable with those achieved on photographic film, i.e. approaching 10^8 bits/sq. inch can therefore be expected.

4.1.5. Laser beam: metal film

A number of machines based on the laser-punch tape technique described in the previous report[1] have now been delivered to users. They achieve a packing density of 17 Mbits per square inch and will work at a transfer rate of about 5 Mbits per second. The intended extension of the technique to helical scan-recording on continuous tape has not yet taken place and it seems doubtful that a transfer rate suitable for television will be achieved.

The thermal evaporation technique has also been used for the recording of holograms on thin metal films.[17] Very intense laser beams are needed.

An alternative approach to laser beam recording on metal film is provided by the Philips Video Long Player (VLP) disc.[18] A low-power laser beam exposes a layer of photoresist, and the recorded pattern of 'pits'* is subsequently produced by etching. Photographs of the disc obtained using a scanning electron microscope reveal that the ultimate resolution of the medium is by no means fully exploited by the 1 micron focused laser beam and imply that this recording technique could also be used for holography.

4.1.6. Laser beams: magnetic films

Work has continued on the thermo-magnetic/magneto-optic recording technique described in the previous report.[1,19] One difficulty arises from the fact that the Faraday or Kerr rotation in the polarisation of the reading beam is very small, and the consequently inefficient reading process can be disturbed by noise and surface

* The pits represent analogue information and are effectively modulated in both frequency and duration.

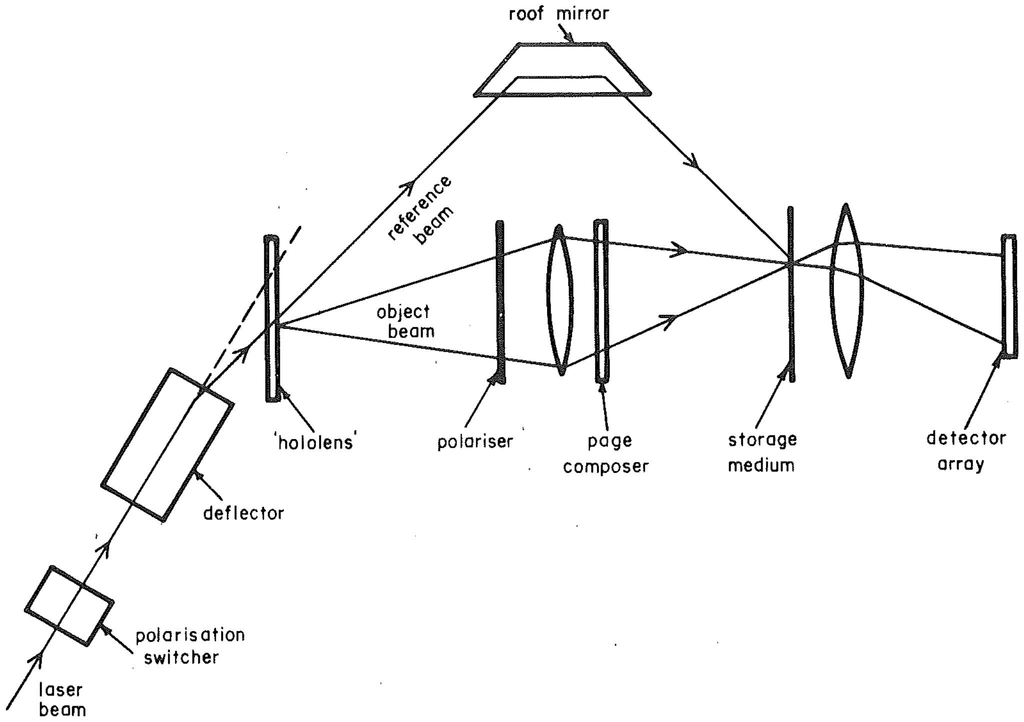

Fig. 4 - Experimental holographic recorder

irregularities. In an experimental bit-by-bit recorder of this type, built by Ampex,[20] the problem was overcome by using tape comprising a cobalt-phosphorous storage film of high coercivity covered first with a thin non-magnetic separation layer and then with a shiny low-coervicity cobalt-nickel-iron surface layer (see Fig. 5). During reading, the surface film is acted upon by the field produced by the storage film together with an externally applied field which has both a d.c. and an a.c. component. These fields combine in such a way that the surface film is either pushed hard into saturation or else switched to and fro by the a.c. component, depending on the direction in which the storage film is magnetised. Thus the recorded information appears in the reflected beam as amplitude modulation of a carrier whose frequency is that of the a.c. field. A considerable increase in signal to noise ratio is claimed when this technique is used.

4.1.7. Laser beam: holographic: magnetic film

The experimental thermoplastic recorder mentioned above was first developed as a magneto-optical recorder using a thin film of manganese bismuthide as the recording medium.[21] Serious difficulties were encountered, however, not only with the reading process, but also with the insensitivity of the medium in the recording mode.[22] Holographic recording requires high resolution and, in magneto-optical recording (as in laser-punch recording), this can only be achieved by using a laser pulse of very short duration, say 20 ns; otherwise the heat pattern spreads in the film before the process of recording is completed. In the present arrangement, this means a laser with a peak power of about 100 kW for a 10 kilobit hologram, i.e. 10 W/bit.[23] On the other hand, the bit-by-bit recorder mentioned above works at about 10 Mbits/sec using a 1½ watt laser.

4.2. Conventional magnetic recording

A previous report[24] on digital magnetic recording described the factors limiting packing density in terms of the width of the replayed pulses corresponding to the spacing of transitions in the two-level recording current. Two factors determine the width of these pulses. One is the blurring of the recorded magnetic transitions on the tape caused by self-demagnetisation effects; the duration of the recorded transition may approximately be described in terms of a 'spread' factor.

$$a = \frac{(B_r)\,C}{2\pi\mu_o(H_c)}$$

where B_r is the retentivity of the medium
C is the thickness
and H_c is the coercivity

It may therefore be reduced either by reducing B_r or C or by increasing H_c. The effective thickness of the coating can be reduced by turning down the record current so as to magnetise only the surface of the medium. B_r can be reduced and H_c can be increased by altering the constituents of the tape. The limit imposed upon a reduction of B_r or C is that either will reduce the replayed signal and thus degrade the signal-to-noise ratio and increase the susceptibility to drop-outs caused by partial separation between the tape and the replay head. A higher value of H_c, on the other hand, demands a higher record current with the danger of saturation of the recording-head pole-tips and difficulties with erasure.

There has been considerable effort devoted to this

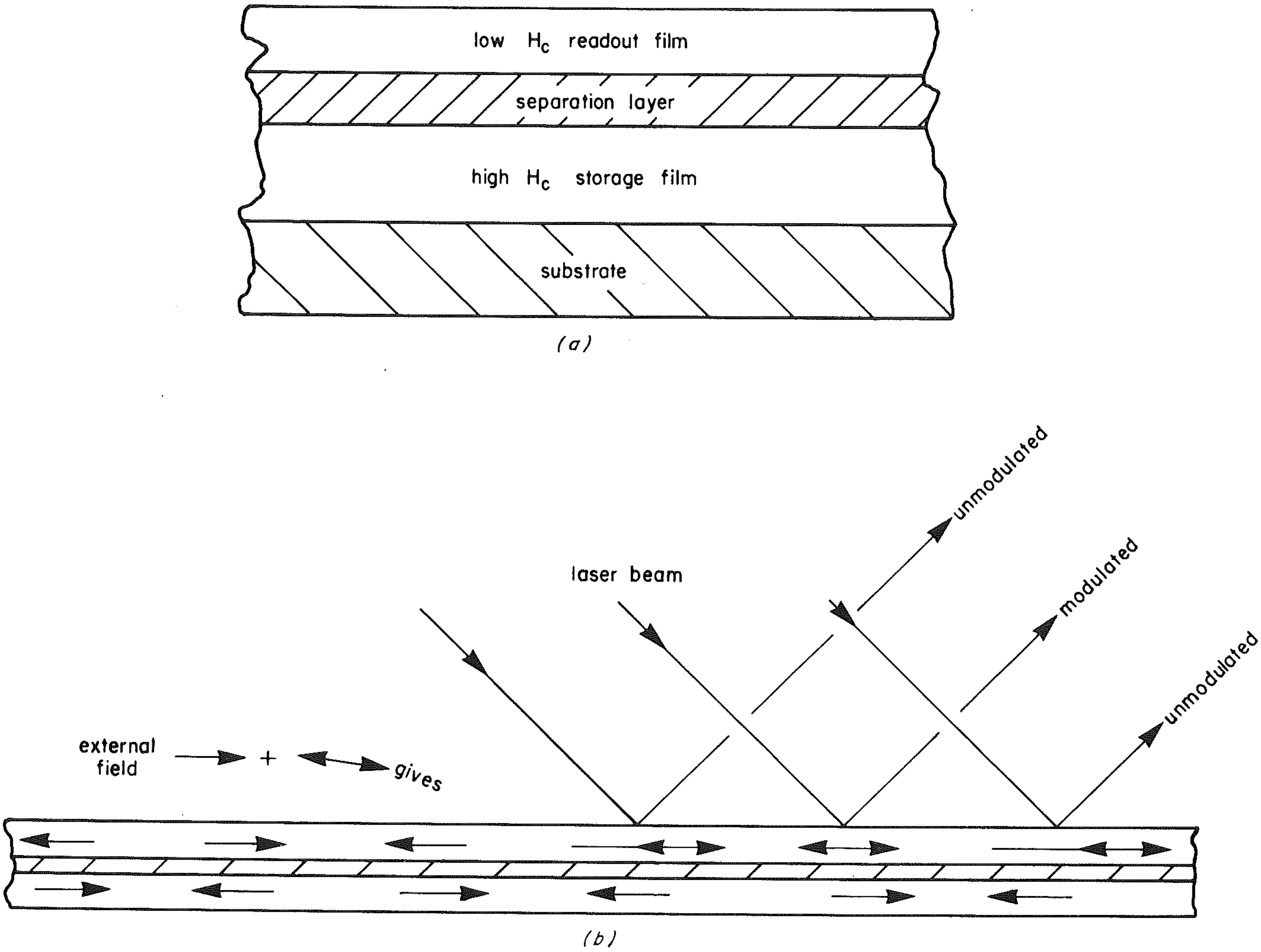

Fig. 5 - Magneto optical recording, method of improving output signal
(*a*) Structure of medium (*b*) Replay technique

problem during the past few years in response to demands for higher packing densities in both analogue and digital recording;[25,26,27] chromium dioxide has been introduced as an alternative to the more common gamma-ferric oxide, while the latter has been doped with cobalt and other materials (the so-called 'high-energy' tapes) and metal films and particles have been tried. In practice, the over-riding constraints are often those concerned with how well the particles can be formed and dispersed within their plastic binder, the cost of the material and the abrasivity of the tape and therefore the head wear. Presently available high-energy tapes have a typical retentivity of 1500 Gauss and a coercivity of 530 Oersteds.*

The other factor limiting packing density is the gap length (i.e. along the axis on the recorded track) of the replay head; replayed pulses are broadened by the aperture effect of the finite reading gap and the latter should therefore be made as small as possible. With each reduction in gap length, however, the gap depth (i.e. normal to the surface of the tape) needs also to be reduced so as to preserve the efficiency of the magnetic circuit. Such a reduction poses serious wear problems and, in order to obtain the required combination of long life and low loss with small well-defined gaps, instrumentation heads have been constructed using ferrite cores fitted with caps made with very hard alloys.[28] More recently, very dense ferrites have been developed using a glass bonding technique that permits the construction of well-defined narrow gaps with shallow pole-tips.[29] All-ferrite heads are already used for single-track helical-scan recording, and multitrack instrumentation replay-heads have begun to be made in this way. This trend will probably continue.[30]

It seems unlikely that a single-track head could be made to work at 100 Mbits/sec or even 50 Mbits/sec, and to cope with these data rates the signal would have to be subdivided into a number of channels operating in parallel. A few heads could be arranged to scan across the tape, say in the manner of a helical recorder, or many more heads could be arranged to record and replay longitudinally. The second of these two approaches is being used in the design of the experimental digital television recorder already mentioned. Multitrack heads have been built which lay down 60 tracks on 2-inch tape or 42 tracks on 1-inch tape. Within each track, densities of more than 20 thousand

* Scotch type 971 high-energy tape.

magnetic 'cycles' per inch are realisable, and it seems probable that data at a rate well in excess of 2 Mbits/sec/track could satisfactorily be recorded at a speed of 120 ips using delay-modulation as the signal code.[31] These arrangements would provide a packing density of about 1 Mbit/sq. inch. Still higher linear packing densities have been claimed using experimental heads capable of 2 MHz at 60 ips and further improvements in track packing densities (i.e. number of tracks per unit tape width) are expected. The upper practical limit of packing density using multi-track longitudinal recording appears to be about 4 Mbits/sq. inch. A similar limit might be approached using multi-track helical scanning, but the potential tracking difficulties associated with such an arrangement might call for impracticably stringent mechanical tolerances.

5. Discussion

The brief summary of current developments given in Section 4 has made it clear that, in the short run, relatively conventional magnetic techniques are most likely to satisfy the requirements of digital television recording. Fig. 6 illustrates that the presently achievable packing density of 1 Mbit/sq. inch contrasts markedly with computer tape recording at 1600 bits per inch with 9 tracks on half-inch tape, but at 100 Mbits/sec. implies a four-fold increase in tape consumption as compared with present high-grade analogue recording. This factor of four would prevent such a system replacing the recorders currently in service.

Further increases in packing densities, perhaps assisted by successful bit-rate reduction techniques might, however, make digital television recording using magnetic tapes and heads a realistic proposition in the not too distant future. It should, however, be borne in mind that the improvements in heads and tape that would contribute towards higher digital packing densities would probably also provide improvements in analogue recording.

What seems certain, however, is that conventional magnetic recording will never be able to compete with the newer technologies so far as packing density is concerned (see Fig. 6). It appears probable therefore that conventional magnetic recording will eventually be replaced. Considering the difficulties that attend electron beam recording, and the progress being made with optical techniques, it seems likely that laser beams will prove to be the more convenient. Moreover, the clear advantages of holographic as compared with bit-by-bit recording point the way to holography as the most satisfactory method of laying down the information.

The biggest imponderable at present is which medium

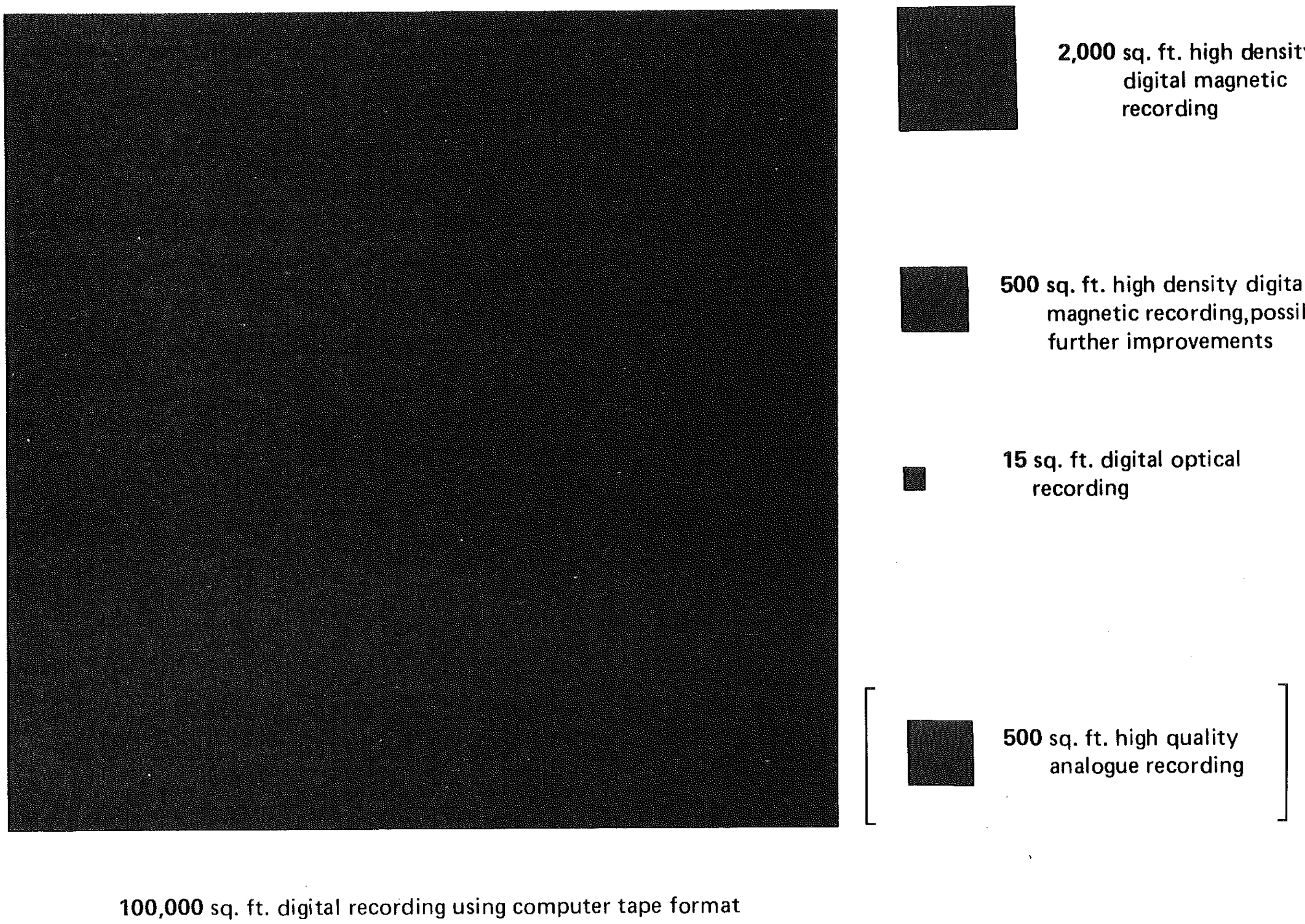

Fig. 6 - Television recording — area of medium required for half-hour programme

will prove best suited to television recording. Laser-addressed magnetic films possess many desirable characteristics – e.g. no image development process, reuseability, selective erasure capability, long storage life. Progress in magneto-optics is, however, slow, and the insensitivity of the medium has so far precluded data rates of the order required for television. RCA's switch from magneto-optical to thermoplastic recording is a significant comment on the relative potentialities of the two media. The thermoplastic medium is not seriously limited in sensitivity, but many problems remain with this medium also; in particular, its suitability for selective rewriting and long term storage have yet to be demonstrated. Photographic film is certainly a possibility, but could only be considered for long term storage.

In this rather nebulous situation it is difficult to make a firm prediction. Evidence to date points to a thermoplastic medium for programme assembly, and photographic film, possibly using a very similar form of recorder, for long-term storage. However, a more suitable magneto-optical medium might be developed which would displace both of these, or some entirely different type of medium, at present the subject of basic research, might emerge. What seems certain is that digital recording by conventional megnetic methods will have been thoroughly explored and probably stretched to the limit before it is seriously threatened by a rival technology.

6. Conclusions

Television recording has much to gain from the application of digital techniques; the digital recorder will provide significant improvements in picture quality, reliability, and operational convenience. Work carried out to date on digital signal-processing suggests that digital television recorders will eventually need to handle data at a rate of about 60 Mbits/sec and that it will be possible with the aid of appropriate coding techniques satisfactorily to conceal the presence of digital errors.

Conventional magnetic recording using presently available components can cope with the data rate required for digital television, but improvements in packing density are required if the advantages of digital recording by this method are not to be offset by an increase in tape cost.

Very large savings in medium consumption are expected, however, from the newer technologies using laser or electron beams. The development of most of these technologies is still at a very early stage, and it is not yet clear which will prove most suitable for the television application. The most promising methods use laser-beam holography employing magneto-optic or photoconductive thermoplastic media. It is anticipated that by the time a laser beam system emerges as a serious contender the limiting performance of conventional magnetic recording will have been reached.

7. References

1. LUNN, J.D. *and* MOFFAT, M.E.B. 1969. Possible techniques for the recording of digital television signals. BBC Research Department Report No. 1969/42.

2. KULCKE, W. et al. 1966. Digital light deflectors. *Proc. IEEE*, 1966, **54**, 10, pp. 1419 – 1429.

3. Deflectors steers laser beam into million-spot matrix. *Electronics*, 1971, **44**, 3, p. 5E.

4. Laser beam deflection. BBC Research Department Report in course of preparation.

5. Holography: a general survey. BBC Research Department Report in course of preparation.

6. Recording using hologram arrays: a general survey. BBC Research Department Report in course of preparation.

7. Digital recording using hologram arrays: low frequency micro-holograms on photographic film. BBC Research Department Report in course of preparation.

8. BARTOLINI, R. et al. 1970. Embossed hologram motion pictures for television playback. *Applied Optics*, 1970, **9**, 10, pp. 2283 – 2290.

9. HELLMEIER, G.H., ZANONI, L.A. *and* BARTON, L.A. 1968. Dynamic scattering: a new electro optic effect in certain classes of nematic liquid crystals. *Proc. IEEE*, 1968, **56**, 7, pp. 1162 – 1171.

10. WATERWORTH, P. *and* CHILTON, G.A.A. 1972. Integrated electro-optic modulator arrays. *Opto-Electron*, 1972, **4**, 3, pp. 339 – 340.

11. MELEN, R. 1973. The tradeoffs in monolithic image sensors: MOS vs CCD. *Electronics*, 1973, **46**, 11, pp. 106 – 111.

12. ENGBERG, E.W. 1970. State-of-the-art wide-bandwidth electron beam analogue recorder and reproducer. Record of the 11th Symposium on Electron, Ion and Laser Beam Technology.

13. NEWBERRY, S.P. 1966. An electron optical technique for large capacity random-access memories. *A.F.I.P.S. Conf. Proc.*, 1966, **29**, pp. 717 – 728.

14. WATERWORTH, P. Holographic data storage. To be published in Inst. of Physics Bulletin.

15. CREDELLE, T.L. *and* SPONG, F.W. 1972. Thermoplastic media for holographic recording. *RCA Rev.*, 1972, **33**, 1, pp. 206 – 226.

16. STEWART, W.C. et al. 1973. An experimental read-write holographic memory. *RCA Rev.*, 1973, **34**, 1, pp. 3 – 44.

17. RAMBERG, E.G. 1972. Holographic information storage. *RCA Rev.*, 1972, **33**, 1, pp. 5 – 53.

18. Philips TV disk, read by light beam, could shape market. *Electronics*, 1972, **45**, 19, pp. 29 – 30.

19. HUNT, R.P., ELSER, T. *and* WOLF, I.W. 1970. The future role of magneto-optical memory systems. 1970. Datamation, April.

20. TREEVES, D. 1972. Magneto-optics: experimental. Annals of New York Academy of Sciences, 1972, 189, pp. 278 – 310.

21. LOHMAN, R.D., MEZRICH, R.S. *and* STEWART, W.C. 1971. Holographic mass memory promise: megabits accessible in microseconds. *Electronics*, 1971, **44**, 2, pp. 61 – 66.

22. COHEN, R.W. *and* MEZRICH, R.S. 1972. Materials for magneto-optic memories. *RCA Rev.*, 1972, **33**, 1, pp. 54 – 70.

23. HUNT, R.P., MAGYARY, A.K. *and* DICKEY, B.C. 1970. Optical scanning for a magneto-optic memory. *J. Applied Physics*, 1970, **41**, pp. 1399.

24. JONES, A.H. *and* CHAMBERS, J.P. 1972. Digital magnetic recording: conventional saturation techniques. BBC Research Department Report No. 1972/9.

25. SPELIOTIS, D.E. 1972. Recent developments in the theory and materials for digital recording. *Intermag*, 1972.

26. MORRISON, J.R. 1972. Particulate materials vs thin film, a system overview. Annals of New York Academy of Sciences, 1972, 189, pp. 69 – 101.

27. SMALLER, P. 1972. Particulate media. Annals of New York Academy of Sciences, 1972, 189, pp. 102 – 115.

28. LEMKE, J.U. 1972. Recent advances in magnetic recording heads; presented at International Aerospace Symposium, Cranfield 1972.

29. LEMKE, J.U. 1972. Ferrite transducers. Annals of New York Academy of Sciences, 1972, 189, pp. 171 – 190.

30. SUGAYA, H. 1968. Newly developed hot-pressed ferrite head. *IEEE Trans. Magnetics*, 1968, **MAG–4**, 3, pp. 295 – 301.

31. HECHT, M. *and* GUIDA, A. 1969. Delay modulation. *Proc. IEEE*, 1969, **57**, 7, pp. 1314 – 1316.

SMW/AMM

Printed by BBC Research Department, Kingswood Warren, Tadworth, Surrey